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Aerodynamics and Acoustics of Rotor Blade-Vortex Interactions

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As part of an international cooperative program, several aerodynamic and acoustic prediction codes have been recently developed to understand the rotor blade-vortex interaction (BVI) noise. Furthermore, a joint validation activity of these prediction codes was performed with the blade surface pressure and acoustic data taken in the German–Dutch Wind Tunnel with the 1/7-scale model AH-1 Operational Loads Survey blades. Careful attention has been given to the detailed flowfield, especially wake structures during BVIs including the miss-distance between vortex and blade, vortex core size, and tip vortex trajectories. The results of flowfield including wake systems from various prediction codes show some quantitative differences, but the acoustic results using these calculated airloads as inputs compare reasonably well with test data.

Introduction

DUE to the current and planned stringent noise regulations for rotorcraft, noise now receives serious attention early in the design process instead of as a problem during production. However, there is still a serious tradeoff problem between noise and rotorcraft performance. Since the rotor provides lift, control, and propulsive forces, the aerodynamic state of the rotor plays an important role in noise generation and also performance of the rotorcraft. Therefore, understanding of the local aerodynamic and dynamic state of the rotor during blade-vortex interactions (BVIs) is essential to predicting the BVI noise and is the main subject of this article.

Over the past years, researchers have developed computational codes and experimental databases for airloads, flowfield, and acoustics to understand the basic rotor noise-generating mechanisms and eventually to control the noise field. This effort has advanced the understanding, modeling, and controlling of the various rotor noise-generating mechanisms. Of these mechanisms the noise generated by BVIs is one of the most complex problems and the capability to predict and modify this BVI noise radiation is far from mature at this time. Although many efforts have made some progress in understanding and controlling this problem, only a few rather qualitative design changes have resulted. The lack of understanding and modeling in accurate wake structure/geometry, especially during BVIs, has been identified. Particularly lacking is the ability to predict vortex core size, miss-distance between the blade and vortex, wake trajectory, and vortex strength. Since there is little experimental data on these available at the present time, many analytical models have assumed different, sometimes unrealistic, wake structure/geometries to get a good correlation with test data.

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Previous experimental and computational efforts are now briefly reviewed. One of the best full-scale tests was the joint U.S. Army and Bell Helicopter flight test program called the Operational Loads Survey (OLS),[1,2] which involved the in-flight acquisition of blade surface pressure distributions and acoustic signatures on an AH-1G. One important finding from this test is that the BVI phenomenon is very impulsive with large blade surface pressure fluctuations that are strongly concentrated at the leading edge of the blade. In fact, these pressure fluctuations are confined to the first 10% of the blade chord.

A 1/7-scale model of the same OLS rotor was tested in the German–Dutch Wind Tunnel (DNW) with pressure-instrumented blades to simultaneously measure blade surface pressures and far-field acoustics,[3,4] investigating the scalability between model- and full-scale tests, including the scaling parameters of BVI noise and the noise directivity pattern.[5,6] From this test, four nondimensional scaling parameters, besides blade geometry and microphone positions, were identified in order to duplicate full-scale data. These parameters are 1) advance ratio, 2) hover tip Mach number, 3) thrust coefficient, and 4) tip-path-plane angle. With respect to the directivity of BVI noise, the acoustic energy has been found to be radiated forward and down approximately 30 deg beneath the rotor plane. A lateral directivity sweep at this 30-deg elevation angle revealed that the pulse amplitudes remain high in the forward direction, 30 deg on advancing and retreating sides.

Using the full-scale OLS flight test data as input, an analytical code[7] was developed to predict the BVI noise radiation using the Ffowcs Williams and Hawkings (FWH) formulation. This analysis resulted in an underestimation in pulse amplitude and an overestimation in pulse width. These discrepancies may be attributed to an inadequate 400-Hz frequency response of the blade pressure instrumentation and from the numerical interpolation scheme of the measured data due to an insufficient number of pressure transducers on the blade.

Using the OLS model-scale DNW test data as input, another analytical code[8] was developed to predict BVI noise again using the FWH formulation. This analysis resulted in the underestimation of the dominant acoustic pulse amplitude. Also, it was shown that the time rate of change of the blade surface pressure during interactions with a vortex determines the amplitude of the resultant peak in the acoustic waveform. At the same time frame a similar approach to calculate the acoustic radiation using the FWH formulation with the OLS model test data as input was performed at DLR.[9]

A computational fluid dynamics (CFD) full potential rotor (FPR) code coupled to CAMRAD/JA has been applied to predict the blade surface pressure distribution and acoustic radiation and been validated with the OLS model-scale rotor DNW test data.[10,11] It was concluded that the accuracy of the predicted surface pressure was heavily dependent on the user-specified vortex core radius and on the predicted geometry of the interacting vortex elements. The core radii used in this analysis were 46 and 8% of the chord and the miss distance depends on the core size; the miss distance decreases as the core size increases. Meanwhile, the researchers at ONERA have also developed CFD codes to predict the BVI aerodynamics and acoustics and validated their results with the OLS model-scale rotor DNW test data.[12,13] This effort has been extended and is reported in this article.

The question is now how accurately BVI aerodynamics and noise can be predicted with the current prediction capabilities and how this BVI noise can be reduced by active blade-control concepts such as higher-harmonic controls. In order to answer some of these questions, the blade surface pressure and noise test data in the DNW with the OLS model-scale two-bladed, rigid rotors[3] was used for code validation efforts. However, the wake structure and geometry were not measured in this test.

In summary, the objective of this article is to carefully examine the effects of miss distance, core size, vortex trajectory, and vortex strength on the blade airload and BVI noise radiation with various computational prediction codes from DLR of Germany, ONERA of France, and the Aeroflightdynamics Directorate (AFDD) of the U.S. Army.

Aerodynamic and Acoustic Prediction Model

AFDD, DLR, and ONERA have independently developed their own aerodynamic and acoustic prediction models using quite different approaches. Each model will be briefly described here with a reference for further details.

AFDD Prediction Model

An iterative coupling scheme between the FPR and CAMRAD/JA codes was developed.[14] The process is started by obtaining a trimmed nonuniform inflow solution with lift obtained from airfoil tables. This is the normal operation of CAMRAD/JA, except that partial wake-influence coefficients are computed in addition to the usual full-wake values. These coefficients are used to obtain partial inflow distribution, which in turn are fed to FPR. The lift distributions so obtained are then fed to the CAMRAD/JA trim loop where the airfoil tables are used to find a lift correction. The process iterates between FPR and the trim loop until convergence of the angle of attack is achieved. Convergence of this scheme is extremely rapid, about two to three iterations.

Once the iteration between CAMRAD/JA and FPR has converged, the lift correction values go to zero and the lift values used for the CAMRAD/JA aerodynamic loads are completely provided by the three-dimensional unsteady FPR code. The highly unsteady and three-dimensional flowfield of BVIs requires a very high-resolution capability over a very small azimuthal range in modeling the interactions. However, in the present form, the CAMRAD/JA code is run in 15-deg azimuthal increments, which is too coarse to represent the realistic BVI events. Therefore, the azimuthal resolution has been improved to 10 deg.

A simple rotor acoustic prediction program (RAPP) utilizes the FWH equation in a form well suited to incorporate blade surface pressures from computational codes such as FPR.[15] This RAPP code contains only monopole and dipole terms with the assumption that BVIs do not result in strong shocks and that the contribution to noise from quadrupoles is negligible.

The RAPP code uses an acoustic lifting line method to model the blade surface loading obtained from the CFD codes. The acoustic lifting line is the quarter chord of the acoustic planform which consists of the locations of the contributing sources, which are found by solving the retarded time equation. In this formulation, the force terms in the FWH equation are modeled as chordwise compact sources with several spanwise source locations along the quarter chord of the acoustic planform.

DLR Prediction Model

The aerodynamic prediction code, S4, was developed[16,17] to calculate the performance, rotor dynamics, unsteady blade loading, and new control laws. In particular, the blade motion calculation for flap, lead-lag, and torsion is uncoupled. The wake system used in this analysis is basically the Glauert wake for first-harmonic analysis, the Mangler–Squire wake for higher harmonic analysis, and the Beddoes wake system for BVI analysis. In this Beddoes model, a tip vortex geometry is prescribed, trailed and shed vortex systems can be implemented, and vortex geometry can be corrected by blade motions.

For aerodynamic calculations, the linear and nonlinear lifting line methods are used with or without the Leiss dynamic stall model. The resolution is up to 2 deg azimuthally and can be easily adopted to any smaller step size with an increase in CPU time. The radial grids are up to 20 elements and can also be easily adopted to a larger number with a further increase in CPU time. The outputs of this code are local velocities at three-quarter-chord along the span, aerodynamic coefficients and forces along the span, flap, lead-lag and twist deflections along the span, and rotor hub forces and moments.

For acoustic calculations the DLR has developed an acoustic code AKUROT[9] using only the linear thickness and loading terms of the FWH formulation with inputs of the source strength resulting from the S4 code.

ONERA Prediction Model

The numerical methods developed at ONERA are performed in three main steps to compute the aeroacoustics of helicopter rotors in descent flight conditions. First, the rotor wake geometry and vortex intensities are computed for a given flight condition. Secondly, the local blade surface pressures are calculated. Finally, the sound radiation for any given microphone position is calculated using an acoustic noncompact formulation with this calculated blade surface pressure distribution as an input.

The rotor wake geometry is calculated by MESIR.[12] In this free wake model, the blade is simulated by a lifting line method. The blade sections are taken into account from their two-dimensional airfoil tables to give the local load for given freestream conditions. The rotor wake is described by the vortex lattice method, and its intensity is determined by the load history on the blade from which the wake comes. An iterative process is used to distort the wake so that the vortex sheet is converged to be tangent to the local convection velocity. Using this method, the BVI parameters such as vortex intensity and miss-distance are obtained. Furthermore, the tip vortex geometry and circulation, as well as the velocity field induced by the inner sheet on the quarter-chord line are stored to be introduced as input to compute the pressure field on the blade.

The blade surface pressure field can be computed by two alternate methods. The first one, ARHIS, has been frequently used. This code[13] is based on a two-dimensional singularity method with inviscid and incompressible flow along with compressibility corrections. Due to these simplifying assumptions, this method is very fast in terms of CPU time, but its main advantage is its capability to predict surface pressure distribution for close BVIs. This feature is obtained from a cloud-vortex simulation of closely interacting vortices. Then the modification of the vortex-induced velocity field due to vortex geometry distribution during a blade-vortex head-on collision can be taken into account.

The second method for computing blade pressure distribution is the FP3D code,[18] which solves the unsteady three-dimensional full potential equation for an isolated blade in forward flight. The influence of other blades and wake is counted through modified boundary conditions on the blade. This method was designed to compute transonic flowfield around a blade tip. However, by coupling MESIR and FP3D, the blade surface pressure distribution due to a BVI can be calculated. The BVI locations and interaction parameters are calculated from MESIR, and the influence of the interacting wake is computed at each FP3D grid point on the blade through a transpiration condition, while the remaining wake influence is computed at the one-quarter-chord line. However, this method requires more CPU time and its current limitation is an inability to properly simulate blade-vortex collisions.

The noise radiation is computed by the PARIS code.[13] This code is based on the FWH equation and calculates thickness noise and uses the predicted blade surface pressure distribution to compute loading noise. The volume of the required airload data has been minimized by introducing a particular and efficient spanwise interpolation scheme in the code. This interpolation identifies the impulsive events and deals with the phase and the amplitude of the signatures radiated by each blade section. The FWH equation is solved in the time domain and is modeled with noncompact sources. This PARIS code requires very little CPU time.

Prediction Results and Comparison with Test Data

A 1/7-scale model of the AH-1 OLS helicopter main rotor was tested in the open-jet anechoic test section of the DNW. The model-rotor blades were mounted on a teetering-hub assembly with the collective, longitudinal, and lateral cyclic rotor inputs through electric swashplate actuators. The geometric characteristics of the 1.916-m-diameter (6.3-ft) model-scale OLS blades and the absolute transducer locations are shown in Fig. 1.

Far-field acoustic signatures and blade surface pressures were simultaneously recorded for various test conditions including low and moderate advance ratios in which blade-vortex interactions are dominant.[3] A total of 10 B&K ¼-in. microphones (Type 4135) were distributed around the rotor in the open-jet core flow. The in-flow microphones positioned forward and down from the rotor-hub plane, typically 3.26 m (10.7 ft) from the rotor hub as shown in Fig. 2, were chosen to compare with the analysis codes.

The rotor was instrumented with 50 miniature pressure transducers: 32 flush-mounted absolute pressure transducers on one of the blades and 18 differential pressure transducers on the second blade. All the microphone signals and selected pressure data were monitored on-line and simultaneously recorded on multichannel, FM, magnetic tape recorders, which

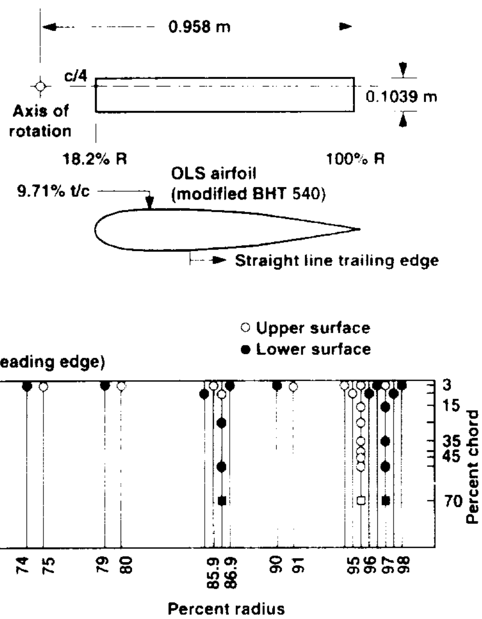

Fig. 1 Model AH-1/OLS rotor characteristics.

Table 1 Test conditions used for code validation

Run number	Advance ratio	Tip-path plane angle, deg	Thrust coefficient	Hover tip Mach number
10014	0.164	1.0	0.0054	0.664
10015	0.146	1.5	0.0054	0.664
10017	0.130	2.0	0.0054	0.664

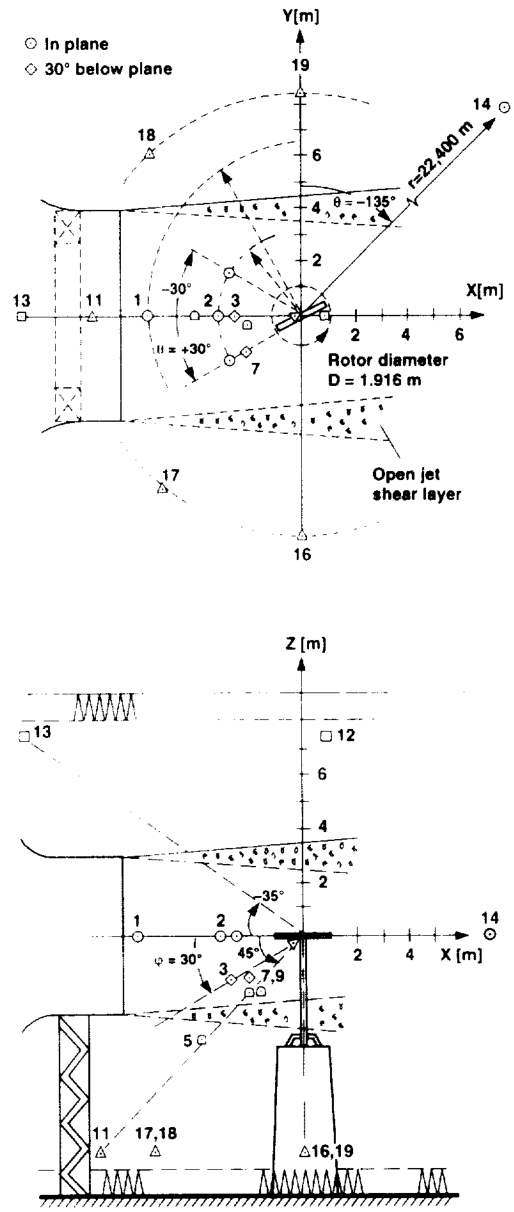

Fig. 2 Microphone locations in the DNW.

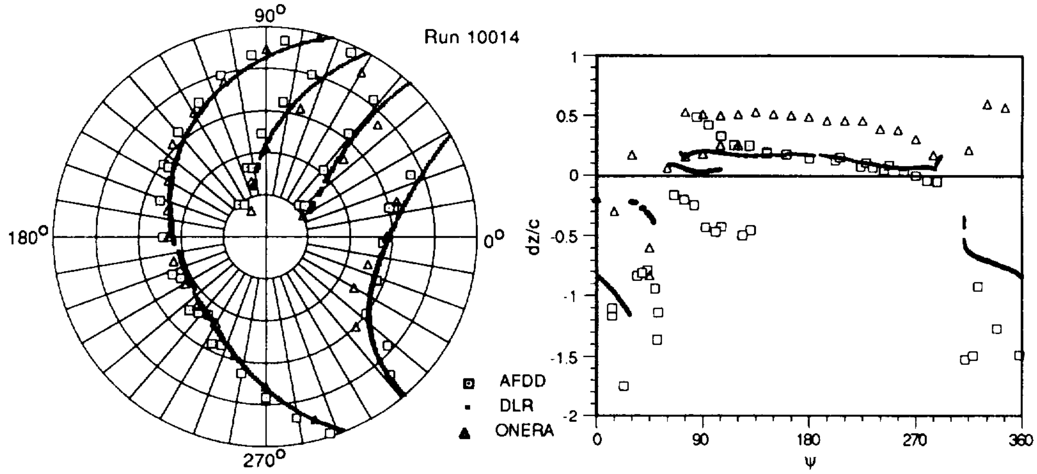

Fig. 3 OLS BVI location on the rotor disk (run 10014 case).

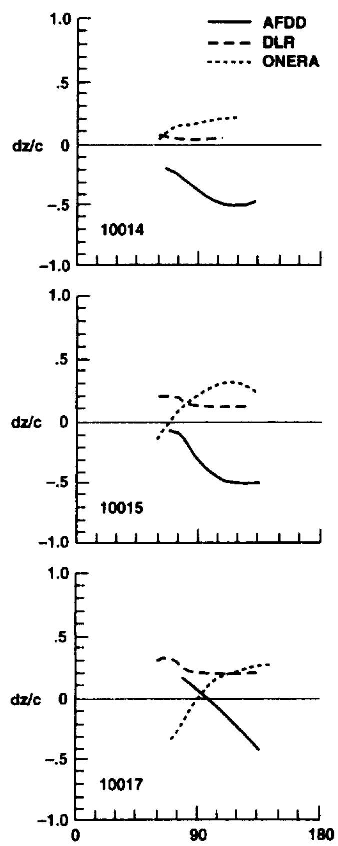

Fig. 4 Miss distances for a dominant interaction.

were set for a recording speed of 76.2 cm/s (30 ips) and a frequency response of 20 kHz.

The following three descent test conditions (run numbers 10014, 10015, and 10017) were chosen to validate aerodynamic and acoustic codes in this study (Table 1). For each test condition, the wake structure and geometry, airload, blade surface pressure distribution, and acoustic signatures are predicted with codes previously discussed and compared to each other with or without experimental data.

BVI Locations and Miss-Distance

The predicted trajectories of all possible BVIs in a top view are presented in Fig. 3 for the run 10014 case, while at the same time the miss-distance between vortex and blade during these interactions is also plotted.

From these figures, several interesting observations can be made. First, either prescribed or free wake makes very little difference in the top view of the BVI trajectories. Secondly, the dominant interaction to the acoustic radiation can be easily found by observing the closest and most parallel vortex trajectory to the blade. However, the prediction of miss-distances is not quite agreeable between codes. In order to highlight the differences, the miss-distance of the dominant interaction for the acoustic radiation is taken out from these figures to plot again in Fig. 4, in which a vortex is located below the rotor plane for one code, is cutting through for another, and located above for the third code. However, the DLR code consistently predicts the vortex location to be above the blade plane, while the AFDD code consistently predicts the vortex to be below the rotor plane for all three flight conditions.

From this analysis, it is concluded that the miss-distance prediction capability is still far from mature and experimental data is badly needed for further validation.

Vortex Core Size

The vortex core size is one of major fudge factors in prediction codes. Even though the core size has been recognized as a critically important parameter, there is no experimental data available at this time to give any guidance on the magnitude. Naturally, every code selects a convenient core size to obtain a good match with experimental data.

The core size (radius) used for this comparison is 20% (0.2) of the chord for all the models except for ARHIS in which the core size depends on the intensity and the age of the vortex and used about 4% of the chord for the present calculation. However, in order to examine the sensitivity of the calculation to various core sizes, the AFDD code is used to calculate the differential pressures with three different values, i.e., 4.6% (0.046), 20% (0.2), and 46% (0.46) of the chord.

Blade Loading and Surface Pressure Distribution

The predicted blade loads at several spanwise locations of the 10014 case with all three codes are shown in Fig. 5. From these plots, a few points can be observed. First, the AFDD code predicts higher overall load levels than the other two codes. Secondly, the DLR code predicts multiple interactions, while the other two codes predict a single strong interaction. Thirdly, predicted occurrences of interaction peaks by ONERA are slightly earlier in azimuthal angles than those by AFDD and then by DLR. This is not quite in accordance with the BVI azimuthal location plots shown in Fig. 3, which predict interactions in the following order: ONERA, DLR, and then AFDD. Overall, the three predictions are quite different in amplitude and shape, but all codes clearly predict the main

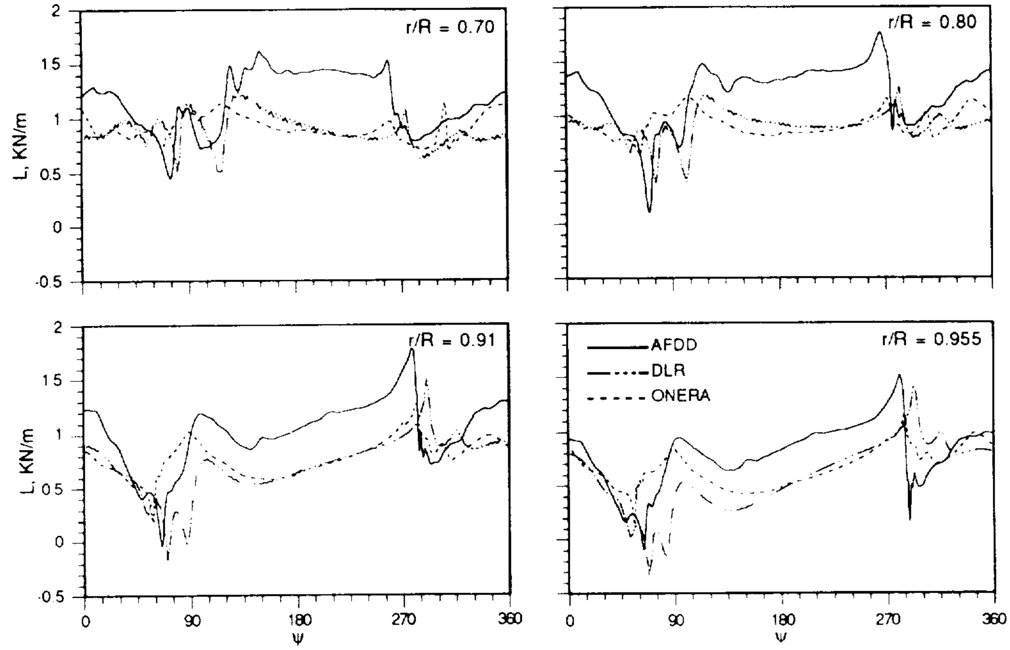

Fig. 5 OLS local blade loading (run 10014 case).

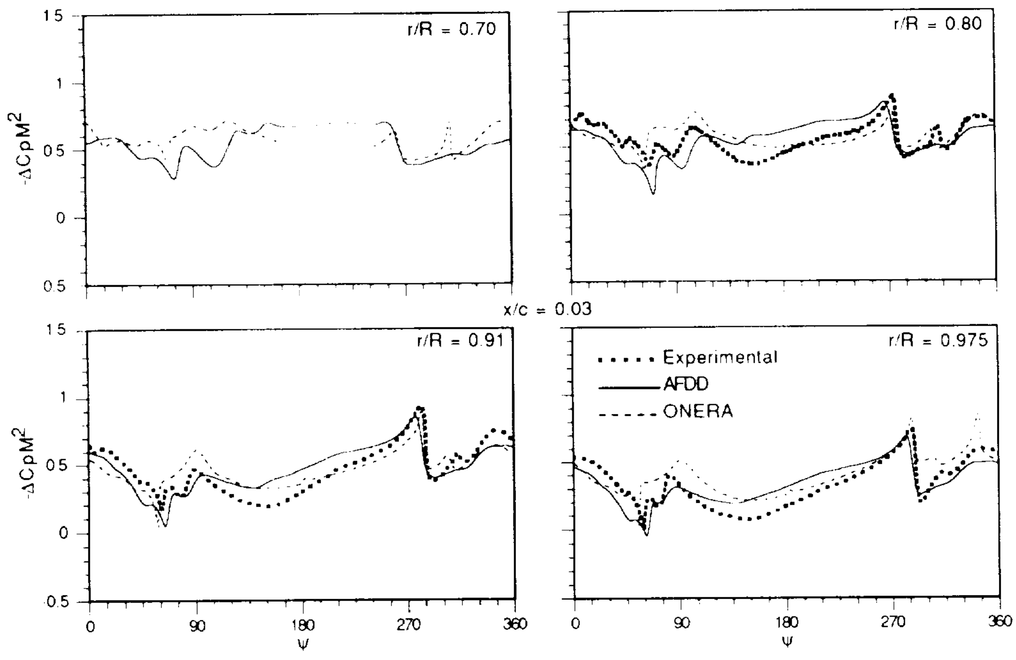

Fig. 6 OLS differential pressures (run 10014 case).

characteristics of interactions in the advancing and retreating sides.

The differential pressure distributions at the 3% chord for four spanwise locations of the 10014 case are compared with the test data in Fig. 6. These differential pressure distributions appear very close to the blade loading distributions, as expected. The differential pressures compare well with experimental data along the span and along the chord, as shown in Fig. 7. The differential pressure level is somewhat underestimated on the retreating blade, but better calculated on the advancing blade side. Very good correlation can also be observed for the phases, showing that the BVI locations are well predicted. Overall, the predictions are reasonably good compared to the experimental data, even though there are some differences in amplitude and the overall level predicted by AFDD is also higher than the test data.

Acoustic Results

It turns out to be difficult to make some general comments about predicted acoustic results vs experimental data. These vary over different flight conditions and different microphone positions. But it can be said that, in a general sense, the analysis codes provide reasonable predictions on the overall acoustic energy level, but not of the details necessary to understand the noise-generating mechanisms and, furthermore, to control the noise. Here, the comparison is made according to specific microphone positions.

For a microphone position in the plane of rotation (microphone no. 2), monopole thickness noise is dominant, as shown in Fig. 8. The predicted thickness noise signatures are well correlated with the test data in pulse shapes, but all codes consistently underpredict the amplitudes by about 30% (for ONERA and DLR) or more up to 50% (for AFDD). How-

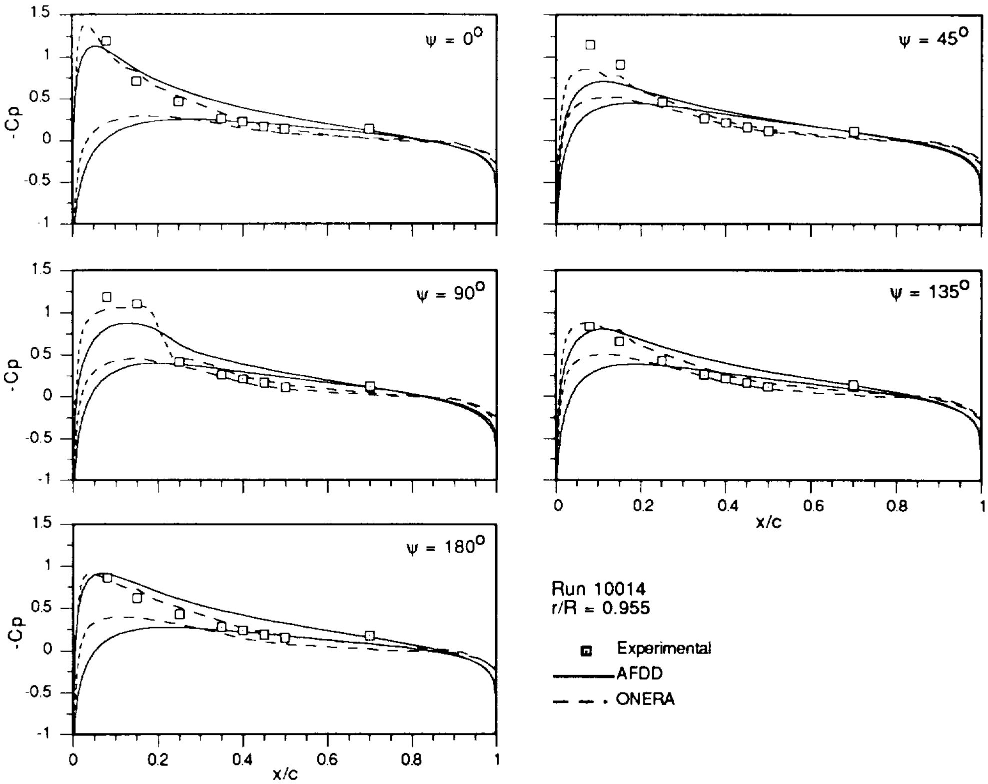

Fig. 7 OLS chordwise pressure distribution (run 10014 case).

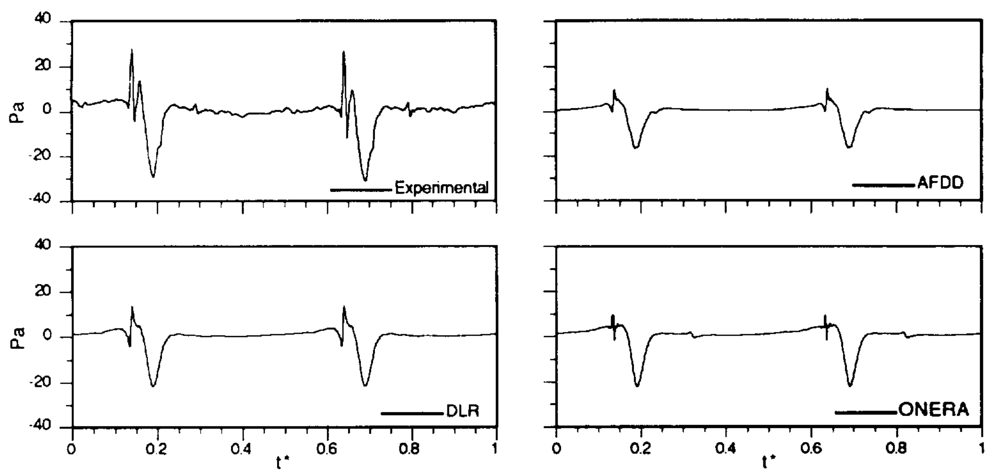

Fig. 8 OLS acoustic pressure time history at microphone 2 (run 10014 case).

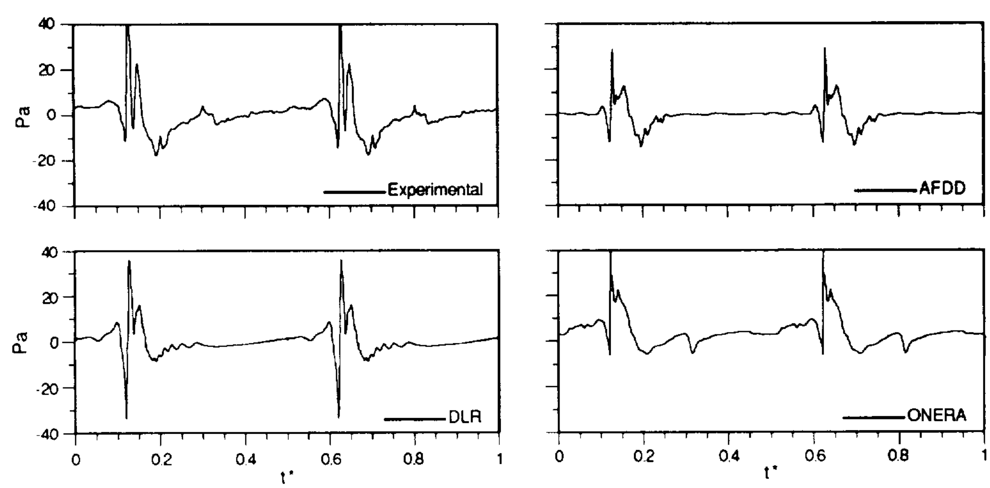

Fig. 9 OLS acoustic pressure time history at microphone 3 (run 10014 case).

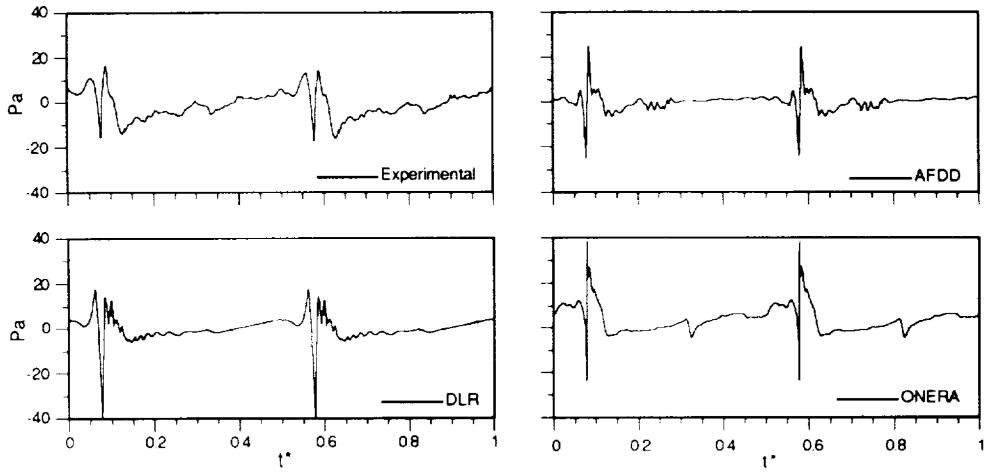

Fig. 10 OLS acoustic pressure time history at microphone 7 (run 10014 case).

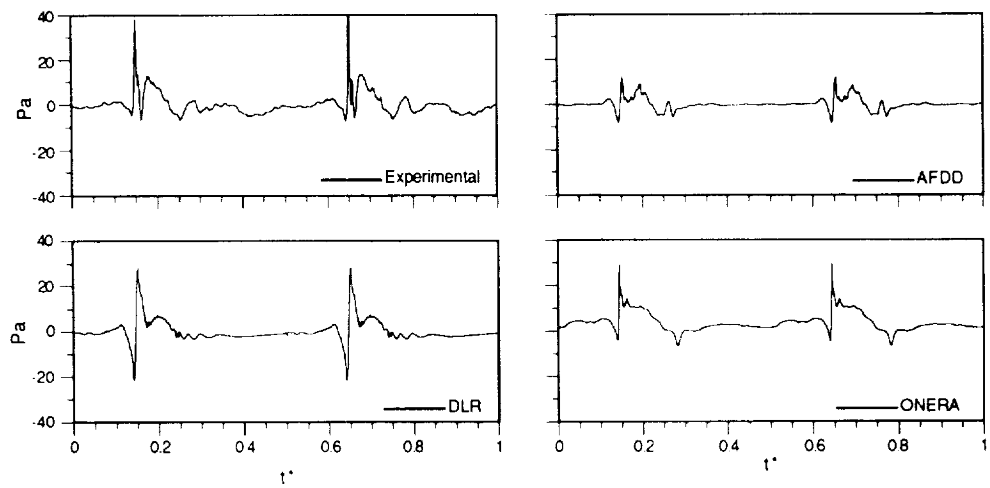

Fig. 11 OLS acoustic pressure time history at microphone 9 (run 10014 case).

ever, for BVI noise predictions for this particular microphone position, the story becomes quite different. Experimental data show relatively strong BVI noise signatures, but none of the codes properly predicts this phenomenon. This may be a big challenge for code developers.

For a microphone located 30 deg below the rotor plane and at the center (microphone no. 3), the predicted results are well correlated with the test data in pulse shapes and amplitudes as shown in Fig. 9. Experimental data show two or three well-defined interaction peaks, of which amplitudes are almost in the same level. However, all three codes generate one single peak, of which amplitude is comparable to that of the experimental data. In general, the DLR code does a better job to predict pulse shapes, while the ONERA code does better for the amplitude.

For a microphone located 30 deg below the rotor plane and on the advancing side (microphone no. 7), the comparison goes awry. Experimental data does hardly show any BVI noise patterns, but all three codes show well-defined BVI noise signatures with large amplitudes as shown in Fig. 10. For a microphone located 30 deg below the rotor plane and on the retreating side (microphone no. 9), experimental data show strong BVI noise signatures, but the codes marginally predict the pulse shapes and amplitudes as shown in Fig. 11.

Concluding Remarks

The differences and similarities of various prediction codes are carefully examined and the various predicted results of BVIs are compared to the OLS model test data. Particular attention has been given to BVI details such as blade surface pressures, far-field acoustics, miss-distance, vortex core size, and vortex trajectories. A few remarks can be made as follows.

There is little difference between free wake and prescribed wake geometry on the prediction of BVI lines and these correlate reasonably well with the limited test data. This is due to the fact that radial contraction has a small effect at these advance ratios. However, the predictions of miss-distance between vortex and blade during interaction vary greatly. The prescribed wake geometry (DLR code) produces a consistent pattern on vortex location located above the rotor plane for different flight conditions, while the free wake geometry (AFDD and ONERA) has more variations over different flight conditions. Unfortunately, no experimental data on this miss-distance is available at the present time.

The vortex core size is another critical parameter in analysis codes. Again, since there is no experimental data available to provide guidance, every analysis code chooses a convenient size, sometimes even unrealistically large, suitable to match experimental data. In the present code validation effort, the core radius is used as 20% of the chord for FPR and S4 and about 4% for ARHIS. Different core sizes are also used in FPR to examine the effect on the airload and acoustic prediction. In general, reducing the core size increases the airload and acoustic amplitudes.

In predicting blade loading and differential pressures, the analysis codes produce reasonable comparisons with test data, but further improvements are needed. With these predicted blade loading and differential pressures as inputs, the acoustic codes based on the FWH formulation predict the BVI noise signatures at the various microphone positions. These acoustic codes capture major qualitative characteristics of noise signatures, but the quantitative details are not yet adequate for design tradeoff studies or for controlling noise signatures.

In summary, the current analytical prediction capability for airload and acoustics for BVIs is not quite mature enough for design tradeoff studies or for controlling BVI noise signature modifications. The major barrier for further improvement is the lack of experimental data of detailed wake information such as miss-distance, vortex core size/strength, and vortex trajectory during interactions. It is extremely important to measure this critical information before generating another database. Without such data the acquisition of another surface pressure and acoustic database will have a very limited usefulness for the BVI problem.

References

[1]Shockey, G. A., Williamson, T. W., and Cox, C. R., "Helicopter Aerodynamics and Structural Loads Survey," 32nd Annual Forum of the American Helicopter Society, Washington, DC, May 1976.

[2]Sakowsky, P. C., and Charles, B. D., "Noise Measurement Test Results for AH-1G Operational Loads Survey," Vols. I and II, Bell Helicopter Co. Rept. 299-099-831, Forth Worth, TX, Oct. 1976.

[3]Boxwell, D. A., Schmitz, F. H., Splettstoesser, W. R., and Schultz, K. J., "Helicopter Model Rotor Blade Vortex Interaction Impulsive Noise: Scalability and Parametric Variations," *Journal of American Helicopter Society*, Vol. 32, No. 1, 1987, pp. 3–12.

[4]Boxwell, D. A., Schmitz, F. H., Splettstoesser, W. R., and Schultz, K. J., "Model Helicopter Rotor High-Speed Impulsive Noise: Measured Acoustics and Blade Pressures," 9th European Rotorcraft Forum, Paper 17, Stresa, Italy, Sept. 1983.

[5]Schmitz, F. H., Boxwell, D. A., Lewy, S., and Dahan, C., "A Note on the General Scaling of Helicopter Blade-Vortex Interaction Noise," 38th Annual National Forum of the American Helicopter Society, Anaheim, CA, May 1982.

[6]Schmitz, F. H., and Yu, Y. H., "Helicopter Impulsive Noise: Theoretical and Experimental Status," *Journal of Sound and Vibration*, Vol. 109, No. 3, 1986, pp. 361–422.

[7]Nakamura, Y., "Prediction of Blade-Vortex Interaction Noise from Measured Blade Pressure," 7th European Rotorcraft and Powered Lift Aircraft Forum, Paper 32, Garmisch-Partenkirchen, Germany, Sept. 1981.

[8]Joshi, M. C., Liu, S. R., and Boxwell, D. A., "Prediction of Blade-Vortex Interaction Noise Using Measured Blade Pressures," AIAA Paper 87-2749, Oct. 1987.

[9]Schultz, K. J., and Splettstoesser, W. R., "Prediction of Helicopter Impulsive Noise Using Measured Blade Pressures," 43rd Annual Forum of the American Helicopter Society, St. Louis, MO, May 1987.

[10]Tadghighi, H., Hassan, A. A., and Charles, B., "Prediction of Blade-Vortex Interaction Noise Using Airloads Generated by a Finite-Difference Technique," 46th American Helicopter Society Annual Forum, Washington, DC, May 1990.

[11]Hassan, A. A., Charles, B. D., Tadghighi, H., and Burley, C., "A Consistent Approach for Modeling the Aerodynamics of Self-Generated Rotor Blade-Vortex Interactions," 49th Annual Forum of the American Helicopter Society, St. Louis, MO, May 1993.

[12]Michea, B., Desopper, A., and Costes, M., "Aerodynamic Rotor Loads Prediction Method with Free Wake for Low Speed Descent Flights," 18th European Rotorcraft Forum, Avignon, France, Sept. 1992.

[13]Spiegel, P., Rahier, G., and Michea, B., "Blade-Vortex Interaction Noise: Prediction and Comparison with Flight and Wind Tunnel Tests," 18th European Rotorcraft Forum, Avignon, France, Sept. 1992.

[14]Tung, C., Caradonna, F. X., and Johnson, W., "The Prediction of Transonic Flows on Advancing Rotors," *Journal of the American Helicopter Society*, Vol. 31, July 1986, pp. 4–9.

[15]Gallman, J., Tung, C., Yu, Y., and Kang, K., "Prediction of Blade-Vortex Interaction Noise with Applications to Higher Harmonic Control," AIAA Paper 93-4331, Oct. 1993.

[16]Van der Wall, B., "An Analytical Model of Unsteady Profile Aerodynamics and Its Application to a Rotor Simulation Program," 15th European Rotorcraft Forum, Amsterdam, The Netherlands, Sept. 1990.

[17]Leiss, U., "A Consistent Mathematical Model to Simulate Steady and Unsteady Rotor Blade Aerodynamics," 10th European Rotorcraft Forum, Den Hague, The Netherlands, 1984.

[18]Costes, M., Desopper, A., Ceroni, P., and Lafon, P., "Flow Field Prediction for Helicopter Rotor with Advanced Blade Tip Shapes Using CFD Techniques," 2nd American Helicopter Society International Conf. on Basic Rotorcraft Research, Univ. of Maryland, College Park, MD, Feb. 1988.